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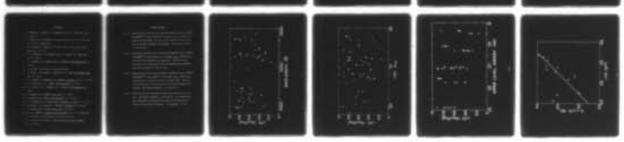

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This report describes measurements of atomic transition probabilities in Fe III, Nd II, Ti I, and Mn I carried out in 1976, and refers briefly to measurements in Fe II, Ni I, Cr I, Pr I carried out since 1971. Method is beam-foil time-of-flight measurement of radiative lifetime of a level, combined with a measurements of the branching ratio for the decay of the level. Purpose and evoluation of the research program over the past six years is discussed.

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FINAL REPORT

Contract N00014-75-C-0424

1 January 1971 - 31 December 1976

Introduction

Contract N00014-C-0424 which terminated on 31 December 1976, was a continuation of Contract N00014-67-A-0094-0022, "Application of Nuclear Techniques to Solid-State and Atomic Physics", which commenced on 1 January 1971. The original contract had two co-principle investigators: Professor J. W. Mayer whose interest was in the solid state physics, and Professor Ward Whaling whose concern was the atomic physics. In 1974 these two activities were separated, and the contract title thereafter is more specific: the measurement of atomic transition probabilities by the beam-foil spectroscopy technique. It is worth noting that the contract which commenced in 1971 was itself a continuation of atomic transition probability research which had been carried out under ONR sponsorship by Professors Whaling and R.B. King that went all the way back to February 1952. Hence, ONR-sponsored studies of atomic transition probabilities have been carried out continuously at Caltech for a period just one month shy of 25 years.

During the six-year contract which has just drawn to a close, our research has evolved from its earlier emphasis on measurement of atomic

radiative lifetimes to a concentration on the determination of atomic transition probabilities. Our studies during 1971-72 showed that nearly all of the visible radiation from the multiply-charged ions produced by our beam-foil source were transitions between Rydberg levels. These peculiar levels were something of a puzzle since at that time they had not been seen in other sources. They have since been seen in laser-produced plasmas, and we now know that they will always, and only, be seen in sources of very low density, the only environment in which they can survive because of their very large cross section for collisional deexcitation. We spent some time and effort attempting to see if these peculiar levels might give some clue to the beam-foil excitation mechanism, but this was not fruitful. Aside from their use as a tool to study the polarizability of the ionic core, and a technical use we have proposed [4] as a device for calibrating the efficiency of detection systems in the far UV, we have found little that we can do with the radiation from the Rydberg states. Because of their tendency to decay through long cascade chains, it is difficult to measure the lifetime of these levels with anything approaching the accuracy with which the lifetime can be calculated from a simple one-electron theory. As a member of a laboratory engaged in the study of stellar evolution and energy production, the fact that Rydberg states are not seen in stars further diminished our interest in them.

During this period of the early 70's a number of other laboratories began to measure atomic lifetimes by the beam-foil method, and there was renewed interest in other methods as well. Many new lifetime values were published in many elements, but almost no one bothered to carry out the next step: the conversion of total transition probability into individual

transition probabilities. When we first set out to measure lifetimes in Fe I, it was our original intent to use the lifetimes to normalize existing tables of relative transition probabilities. We soon discovered that the published relative transition probabilities in Fe I were quite unreliable, despite the fact that the iron spectrum was the most extensively studied of all spectra. Not only were the absolute values inaccurate as has been widely suspected, the measurements of the source temperature, and hence the relative values, were also in serious error. This discovery convinced us that lifetime measurements alone were not enough, that we must also remeasure the relative transition probability as well. Our first efforts to use a high-resolution 21' Rowland spectrometer for this purpose taught us that a two-channel instrument was needed: one channel to measure the intensity of the various decay branches, one channel to monitor the intensity of the source over the long periods of time required to measure ten or fifteen decay branches from a single level. We were fortunate to have on hand a large (5-meter) Paschen-Runge spectrograph which can accomodate any number of detectors. During 1971-73 we modernized this instrument by fitting it with photomultipliers and pulse counting electronics. This spectrometer, with subsequent modifications to extend its wavelength range and facilitate rapid calibration, is without doubt the foremost instrument in the world for measuring atomic branching ratios, and it has influenced the direction our research has taken in recent years. To exploit this facility we have made extensive use of undergraduate students to convert lifetimes measured elsewhere into atomic transition probabilities. Several of the publications [1, 2, 5] on the attached list are of this sort.

Our original motivation in taking up beam foil spectroscopy was astrophysical, and our astrophysical interests have influenced the selection of problems and the methods used to attack them. For example, we have used the very precise published measurements of the solar spectrum to check our laboratory measurements: the relative intensitites we measure in the laboratory should be related to the relative intensities of the Fraunhofer lines in the sun. Unfortunately, the complexities of the solar curve-of-growth are such that one cannot dispense with the laboratory intensity measurements entirely (although some astronomers have tried to do this). However, one can check the internal consistency of laboratory measurements by comparing them with the solar equivalent widths. In order to carry out such comparisons, we have established a collaboration with the Kitt Peak National Observatory which has given us access to their solar spectra and their spectrum synthesis codes by which the equivalent widths are extracted. On three occasions in the past three years, students from this laboratory have visited Kitt Peak to get this solar data. A by-product of such comparisons is a measure of the solar abundance of the element under investigation. In this way we have measured the abundance of solar Fe, Cr, Ni, Pr, Ti, and Nd, and Mn is in progress.

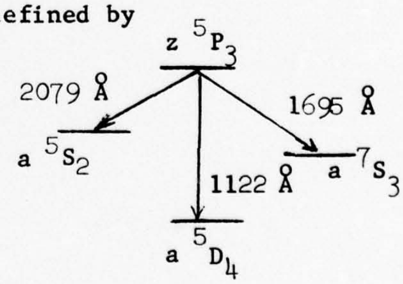
In the sections which follow we will give a more detailed picture of the specific problems studied during the past twelve months. Our principle effort has been to extend our work into the vacuum ultraviolet. Until recently the VUV has been of little interest to astronomers who were limited by the earth's atmosphere to wavelengths longer than 3000Å. Consequently, almost nothing is known about transition probabilities in the VUV, at least for the abundant elements that dominate astrophysical spectra. This is a

wide open, virgin field and several laboratories (notably Aarhus, Princeton, Stockholm) are trying to skim off the cream. The competition adds some interest and urgency to this research.

Research During the Past Year

(1) Fe III. Iron is the most abundant of the heavy elements, and iron lines dominate astrophysical spectra. One of the prominent absorption lines observed by the Copernicus orbiting observatory is the 1122Å resonance transition between the ground level of Fe^{2+} and its lowest (odd-parity) excited level $z\,^5P^o_3$. The strength of observed absorption lines gives the product: (number of Fe^{2+} ions between source and observer) X (transition probability for λ1122). To determine the density of Fe^{2+} ions in interstellar matter, one need only determine the transition probability for the 1122Å transition. Our method (it is also the one being used elsewhere — it seems to be the only way to get at transition probabilities for multiply-charged ions) is to measure the lifetime T of the $z\,^5P^o_3$ level by the beam-foil time-of-flight method, and then measure the relative intensity of the three branches by which this level decays. The transition probability A(1122Å) = BR(1122Å)/T, and the branching ratio BR(1122Å) is defined by

$$BR(1122\text{Å}) = \frac{I(1122\text{Å})}{I(1122\text{Å}) + I(2079\text{Å}) + I(1695\text{Å})}$$



where I(λ) is the observed intensity $I_{obs}(\lambda)$ of the line at wavelength λ corrected for the efficiency of our spectrometer detection system: I(λ) = $I_{obs}(\lambda)$/eff(λ). As we will point out below, the measurement of eff(λ) is the most difficult part of this experiment.

We have measured the lifetime T of the $z^5P^o_3$ level by observing the strong 2079Å branch. This wavelength is accessible to the Jarrell-Ash spectrometer which we have set up for use on neutral and singly charged ions which typically radiate at longer wavelength. Our value is 0.9 ± 0.1ns. This value represents the average between a value of 1.0 ns from three measurements at 800 keV incident beam energy, and 0.8 ns from four measurements at 1.0 MeV. We are troubled that our result appears to depend on bombarding energy and we hope to investigate this matter further.

So far as we know, this is the only measurement of the $z^5P^o_3$ lifetime. The Stockholm and Princeton groups who excite the Fe spectrum by pulsed electron bombardment of $Fe_2(CO)_5$ gas had, at last report, not succeeded in exciting this level. The Aarhus beam-foil spectroscopists have submitted for publication several lifetimes in Fe III, but they have not yet been able to measure the $z^5P^o_3$. A new beam-foil group at Harwell has recently set up equipment to measure Fe II lifetimes. Their equipment appears to be superior to our own here at Caltech, and we have been in correspondence with them with the hope that they can confirm our value and very likely improve on the precision of our value.

Branching Ratio. The beam foil source is inherently weak and not suitable for branching ratio measurements. We have constructed a pulsed hollow cathode source which excites the Fe III spectrum and at the same time suppresses Fe I and II. The pulse frequency of 20 per second is much faster than the 1 second-time constant of our detector so that the discontinuity of the source is no problem. The current and voltage of the ~10-microsecond pulses is hard to measure because of unavoidable inductance in the circuit leads, but the peak current appears to be greater than 900

amperes. The only fault we have found with the source is the rapid erosion of the cathode which requires frequent replacement.

The calibration of the vacuum spectrometer used for the branching measurements has proven to be quite difficult. We purchased two deuterium arc lamps and arranged with the Bureau of Standards to calibrate their light output over the range 3000 - 1670Å, the shortest wavelength NBS can calibrate. One lamp is kept as a reference and used only to check the output of the lamp actually used to calibrate the spectrometer. To extend the calibration down to 1100Å, we use our regular hollow cathode in the same geometry used to scan the Fe III lines, but we replace the argon carrier with a mixture of 10% H_2 in argon. Argon in the $4s(3/2)^o_{J=1}$ level, the upper level of the Ar I resonance line, can readily transfer its excitation energy to the ($\nu' = 3$) vibrational level of the first excited electronic state of the H_2 molecule because of the almost equal energy of these two levels. One then observes the $\nu''(\nu' = 3)$ vibrational progression of the $B^1\Sigma_u^+ \rightarrow X^1\Sigma_g^+$ transition, with members from 1063Å for the (3,0) member, 1116 for the (3,1) member, 1162Å for the (3,2) member, on up to 1672Å for the (3,12) member. This progression, with a common upper level, radiates lines with an intensity that is proportional to the transition probability, and the transition probability can be calculated for a simple molecule like H_2. All we need do is observe these lines in our spectrometer to determine the relative detection efficiency of our system. This calibration arrangement recommends itself because we use the same source geometry for calibration and for measurement. During the summer we carried out observations down to 1322Å, the (3,5) member, but we could not see the (3,4) member at 1268Å. We purchased a grating blazed at 1215Å which was delivered in November, and

with this new grating we have been able to extend the calibration to 1162Å, but we are still 40Å short of our goal in spite of a number of modifications to our spectrometer to improve the transmission and reduce scattered light.

We are being forced to the conclusion that we must give up our simple hollow cathode source as a means of exciting the H_2 spectrum, and go to a capillary source which is capable of much greater brilliance. The rapid decrease in detection efficiency between 1200 and 1100Å makes it impossible to estimate a value for the branching ratio for the 1122Å line from the data we now have in hand.

(2) Manganese I. Tom Greenlee has completed his study of Mn I and is now writing his doctoral thesis. During the past year he has compared his laboratory transition probabilities with the intensity of the Mn I lines in the Kitt Peak solar spectrum. Five of the 80 lines that he studied are unusually clean in the solar spectrum. These five lines yield a solar Mn abundance of $\log(N_{Mn}/N_H) + 12 = 5.45 \pm 0.04$. This value, confirms the currently accepted abundance, and his uncertainty is much smaller. It is likely that in the course of analyzing this result for his thesis, he may need to increase the uncertainty to allow for uncertainties in the solar model assumed in the calculation.

(3) Neodymium II. Robert S. Maier, an undergraduate student, measured branching ratios and transition probabilities for 60 transitions in Nd^+. He went to Kitt Peak during the summer and used their spectrum synthesis codes to measure the solar equivalent width at disk center for 12 of these lines that are seen in the sun. With these new widths and transition probabilities, he computed the photospheric neodymium abundance

to be log $(N_{Nd}/N_H) + 12 = 1.26 \pm 0.14$. This value is a factor of four lower than the two most recently published measurements. The difference between our result and the earlier values lies entirely in the transition probabilities, since our equivalent widths agree with the widths used in the earlier papers. With our 1975 measurement of the solar Pr abundance, we are able to compare the solar Nd/Pr ratio with that found in meteorites: the agreement is very good, providing further evidence that meteoritic material is typical of solar material. It should be noted that this investigation of Nd made use of lifetimes measured at Aarhus. A paper describing our Nd results has been submitted for publication in the Journal of Quantitative Spectroscopy and Radiation Transfer; a preprint is appended to this report.

(4) Titanium I. Our study of transition probabilities for 103 lines in Ti I has been completed and a paper reporting this work has been accepted for publication in the Astrophysical Journal.
This paper draws two conclusions:

(a) The recent (1975) revision of the transition probabilities in Ti I published by the National Bureau of Standards is in serious error. For the weaker lines (transition probability $\leq 10^6$ sec^{-1}) the NBS values are too large by a factor of 3. The NBS compilers relied heavily on erroneous values from Kiel University. We have been in correspondence with the Kiel group to attempt to discover the source of the trouble. It appears to stem from self-absorption in their light source or from a nonlinearity of their detectors (photographic) induced by saturation under strong illumination.

(b) We derived a new value of the solar Ti abundance of $\log(N_{Ti}/N_H) + 12 = 4.98 \pm 0.15$, a value of N_{Ti}/Si ratio. In our paper we consider the effect

of different solar models on the derived abundance, and we derive the abundance in two different ways: from fine analysis of equivalent widths we find 4.97, and from line profile fitting we find 4.98. The uncertainty quoted above comes largely from the 15-25% uncertainty in the radiative lifetimes on which our transition probabilities are based.

Personnel

Ward Whaling, Principal Investigator (1 January 1971 - 31 December 1976)

John N. Scalo, Postdoctoral Research Fellow (1 January - 31 December 1974)

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Don Brotmarkle, undergraduate student (April - October 1976)

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   Astrophysical Jouranl, March 1977.

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   Ward Whaling
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TRANSITION PROBABILITIES IN Nd(II) AND THE SOLAR NEODYMIUM ABUNDANCE*

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SUBMITTED TO THE JOURNAL OF QUANTITATIVE SPECTROSCOPY AND RADIATIVE TRANSFER

ABSTRACT

We have measured branching ratios for all the known transitions from nine levels in Nd^+. We use the known mean lifetimes of four of these levels to compute transition probabilities for 60 transitions. We have measured the solar equivalent widths of 12 of these lines on the Preliminary Edition of the Kitt Peak Solar Atlas and compute a photospheric Nd abundance $\log (N_{Nd}/N_H) + 12 = 1.26 \pm 0.14$, using the solar model parameters of RIGHINI and RIGUTTI based on the MUTSCHLECNER model. The solar lines used in this computation are weak ($W/\lambda < 3 \times 10^{-6}$), and the derived abundance has little dependence on the uncertainties of the solar model.

1. INTRODUCTION

ANDERSEN et al.[1] have recently measured by the beam-foil time-of-flight method the mean radiative lifetime of four levels in Nd (II): $w^6K^o_{9/2}$, $w^6K^o_{17/2}$, $w^6K^o_{19/2}$, and $x^6I^o_{9/2}$. To extract individual transition probabilities $A_{u\ell}$ from their lifetime values $\tau_u = 1/\sum_\ell A_{u\ell}$, we have measured the decay branching ratio, $BR_{uk} = A_{uk}/\sum_\ell A_{u\ell} = A_{uk}\,\tau_u$, for each of the classified downward transitions from each of these levels. We have also measured branching ratios and transition probabilities for the decays of the levels $w^6K^o_{13/2}$, $w^6K^o_{15/2}$, $x^6I^o_{11/2}$, $x^6I^o_{15/2}$, $x^6I^o_{17/2}$, for which we estimate the lifetime by comparing the total intensity radiated by each of these levels with the intensity radiated by other levels of known lifetime in the same term. A number of the transitions we have measured are seen in the solar spectrum. We have remeasured the solar equivalent width for twelve of these lines as they appear at disk center on the Preliminary Edition of the Kitt Peak Solar Atlas.[2] From the widths and transition probabilities we compute a photospheric Nd abundance. Because the solar lines we have used are weak, our Nd abundance value should have little dependence on the uncertainties of the solar model that enter the abundance calculation.

2. EXPERIMENTAL METHOD AND RESULTS

The Nd (II) levels were excited in a hollow-cathode discharge in argon. A 3 mm-diameter cavity drilled in an aluminum cathode contained fragments of Nd foil (0.999 purity). The walls of the cavity quickly became coated with sputtered Nd; even the strongest $A\ell$ lines caused no interference. Also self-absorption was looked for and found not to be appreciably present. The source geometry and the two-channel Paschen-Runge spectrometer used for our

branching measurements have been described by LENNARD et al.[3] For the Nd measurements reported here, EMI 9783B photomultipliers were used in both the measuring and monitor channels. The detection efficiency of the measuring channel was calibrated over the wavelength range of interest by observing its response to a commercial tungsten-ribbon radiance standard, and the linearity of both channels was tested by the two-source method. The calibrated measuring channel was then scanned over all known decay branches from an upper level to measure their relative intensities while the monitor channel, set to detect a strong, well isolated line from the upper level, monitored and recorded the source intensity. Variations in source intensity may be considerable over the period of several hours required to measure all of the decay branches. The measuring channel line profile, fixed by the spectrometer slits, was 80 mÅ FWHM in first order, sufficient to separate the lines of interest.

The observed photon intensity was corrected for the detection efficiency to yield the true photon intensity $I_{u\ell}$, and the branching ratios were computed from the definition $BR_{uk} = I_{uk}/\sum_{\ell} I_{u\ell}$. In the sum we include all transitions from the upper level as classified by ALBERTSON et al.,[4] who provide the most recent classification of these levels' decay branches. They are listed in Table 1. A basic assumption of this experiment is that our sum includes all transitions which contribute significantly to the decay of the level. A number of allowed E1 transitions between our upper levels and known levels in lower terms are too weak to be observed in our spectra or in the work of MEGGERS et al.[5] We assume that these unobserved branches, less than one percent as strong as the strongest decay branches, contribute insignificantly to the total transition probability. Also, the upper levels we consider are at most 31 kK above the ground level, so that there are no energetic

transitions beyond the range of the earlier searches of the Nd spectrum. We cannot rule out the possibility of longer wavelength transitions to unknown even terms at higher excitation energy, but one may expect that such low-energy transitions would have low probability.

The designations we have used for the levels in Table 1 differ from those used by ALBERTSON et al.[4] because of the discovery[6,7] of lower odd sextet terms since the earlier analysis. Thus ALBERTSON'S term z^6K^o we now designate w^6K^o as three lower odd sextet terms are now known. In column 1 we list the original designation of ALBERTSON et al. in brackets beside our designation.

In Table 1 we list the experimental branching ratios BR_{ik} and the transition probabilities $A_{ik} = BR_{ik}/\tau_i$ computed from these branching ratios and the mean radiative lifetime τ_i measured by ANDERSEN et al.[1] and listed in the first column. In the w^6K^o term, ANDERSEN et al. measured the lifetimes of the levels with J = 9/2, 17/2, and 19/2, but they did not measure the lifetime of the levels with J = 13/2 and 15/2. We have estimated the lifetime of these latter two levels by a method first introduced by ROBERTS et al.[8] for comparing the lifetime, or total transition probability, for two levels in the same term on the assumption that the population of two levels within the same term follows statistical equilibrium. Thus for the two levels $w^6K^o_{13/2}$ and $w^6K^o_{17/2}$

$$\frac{\tau_{13/2}}{\tau_{17/2}} = \frac{\sum_i A_{17/2,i}}{\sum_k A_{13/2,k}} = \frac{N_{13/2} \sum_i I_{17/2,i}}{N_{17/2} \sum_k I_{13/2,k}} = \frac{g_{13/2}}{g_{17/2}}\, e^{-\alpha(E_{13/2} - E_{17/2})} \frac{\sum_i I_{17/2,i}}{\sum_k I_{13/2,k}} \;. \quad (1)$$

The total intensities $\sum_k I_{nk}$ are measured in this experiment, the g_n are the statistical weights, and the E_n are the known excitation energies of the two levels. For the coefficient α we use a value 1.44 eV^{-1} determined by

measuring the relative intensity of transitions of known transition probability from two levels ($w^6K^o_{17/2}$ and $w^6K^o_{9/2}$) of different excitation energy. By this procedure we have estimated lifetimes for the w^6K^o levels with J = 13/2 and 15/2 in terms of the $w^6K^o_{17/2}$ lifetime. Similarly we have estimated the mean lifetime of the x^6I^o levels with J = 11/2, 15/2, and 17/2 in terms of the mean lifetime of the $x^6I^o_{9/2}$ level, which was measured by ANDERSEN et al.(1) The lifetimes we find in this way are listed in column 1 of Table 1 in brackets to distinguish them from directly measured lifetimes. The experimental uncertainty in the directly measured lifetimes is about ± 30%. We have increased this uncertainty to ± 40% for the lifetimes estimated by this procedure of comparing total radiated intensity. Because the uncertainty in the experimental branching ratios is always smaller than the uncertainty in the mean lifetime, the uncertainty in the transition probability is approximately the same as the uncertainty in the lifetime. For the medium strong branches used in our solar abundance determination below, the uncertainty in the branching ratio is no more than ± 10% of the value quoted in column 5 of Table 1.

Our transition probabilities are compared with those of CORLISS and BOZMAN(9) (CB) in Figure 1 as a function of wavelength, in Figure 2 as a function of line strength, and in Figure 3 as a function of the excitation energy of the upper level. Figures 1 and 2 indicate a considerable experimental spread but no systematic trends. We conclude that the calibration of our detection efficiency and the dynamic response of our detecting system are consistent with those of MEGGERS et al.(5) on whose measurements the CB transition probabilities are based. Figure 3 shows evidence for a systematic deviation that increases with increasing excitation energy. We conclude that CB used an incorrect source temperature in the analysis of their results. Consequently, the mean deviation of 0.61 dex evident in Figures 1 and 2 may

not apply to transitions from levels at excitation energies different from those measured here.

For λ3863.33 CB find a transition probability several times larger than the value we measure. We believe that MEGGERS et al.[5] did not resolve λ3863.33 from the line at 3863.40 which we find to be several times as strong as λ3863.33.

III. SOLAR NEODYMIUM ABUNDANCE

Many lines due to transitions to the w^6K^o and x^6I^o terms are seen in the Sun and one can derive a photospheric abundance from the transition probabilities reported here. In order to remain in the linear régime where the relation

$$N_{Nd}/N_H = W_\lambda/gf\,\Gamma\,\lambda \qquad (2)$$

holds, we selected the 16 transitions for which MOORE et al.[10] find $\log(W_\lambda/\lambda) \leqq -5.5$. We attempted to remeasure the equivalent width of these lines at disc center on the Preliminary Edition of the Kitt Peak Solar Atlas[2] using the KPNO non-linear spectrum synthesis code, and good fits were obtained for 12 of these lines. Our measured equivalent widths are listed in column 9 of Table 1. They may be compared with the equivalent widths of MOORE et al.[10] from the Utrecht Atlas in column 10, along with a few values measured by GREVESSE and BLANQUET[11] on Jungfraujoch spectra. The computed value of the photospheric Nd abundance, $\log(N_{Nd}/N_H) + 12$, appears in column 11. In computing the abundance from Equation (2), we used the solar model parameter Γ as evaluated by RIGHINI and RIGUTTI[12] from the MUTSCHLECNER solar model[13] for nine of the lines, and

as interpolated by us from their values for the remaining three lines.

The values of W_λ/λ are plotted on a curve of growth in Figure 4. There is little scatter save for the points representing λ5372 and λ5486. These two lines indicate a solar Nd abundance several times greater than that implied by the other lines. As the transition probabilities for these lines do not appear remarkable on Figures 1-3, on which they are plotted as crosses, we attribute the deviation to unresolved blends in the solar spectrum. An unresolved blend in our branching measurements would have reduced the abundance below its true value. It is noteworthy that these two lines are from different upper levels, and that both levels' lifetimes were measured directly by ANDERSEN et al.,(1) not derived by our indirect method.

The logarithm of the mean value of N_{Nd}/N_H based on our measured transition probabilities and the KPNO equivalent widths for ten lines (excluding λλ 5372 and 5468) is 1.26 - 12. The dominating uncertainty entering the calculation of the abundance is the ~ 0.14 dex that comes from the measured lifetimes through the transition probabilities. This uncertainty is consistent with the standard deviation of ±0.14 of the individual abundance values in column 9. For the very weak lines such as those we have used, it is our experience that all of the current solar models yield nearly the same abundance,(14) and we believe that any error introduced by our use of the MUTSCHLECNER model is smaller than the ±0.14 dex uncertainty that we assign to our Nd abundance value.

RIGHINI and RIGUTTI(12) obtained a photospheric Nd abundance of 1.93 ± 0.36 using the solar equivalent widths of MOORE et al.,(10) and GREVESSE and BLANQUET(11) found an abundance of 1.82 ± 0.12 using widths from the Jungfraujoch spectrum. Both of these earlier determinations were based on the transition probabilities of CORLISS and BOZMAN.(9) ANDERSEN et al.(1) proposed a new

value of 1.23 which they obtained by correcting, on the basis of their lifetime measurements, the CORLISS and BOZMAN oscillator strengths for two transitions used by GREVESSE and BLANQUET. Our result of 1.26 ± 0.14 confirms their proposal. ROSS and ALLER[15] adopted ANDERSEN et al.'s value in their recent critical survey.

If we divide our N_{Nd}/N_H ratio by the solar N_{Si}/N_H ratio of 4.5×10^{-5} adopted by ROSS and ALLER, we find for the solar N_{Nd}/N_{Si} ratio a value 4.1×10^{-7}, somewhat lower than CAMERON'S[16] meteoritic value of 7.8×10^{-7}. The uncertainties in the silicon abundance can be avoided by comparing the solar Nd abundance with that of Pr which we have measured recently by the same method.[17] We find the photospheric Nd/Pr ratio to be 4.0, in satisfactory agreement with CAMERON'S meteoritic value of 5.2.

ACKNOWLEDGMENTS

We are indebted to the Kitt Peak National Observatory and to Larry Testerman for their assistance in extracting equivalent widths from their solar spectra. One of us (RSM) wishes to thank the Richter Trust for support during part of this research.

Table 1. Branching ratios and transitions probabilities for nine levels in Nd (II). The level designations in brackets in column 1 are from ALBERTSON et al.,[4] as are the wavelengths in column 2. The level energies in column 1 are from BLAISE et al.[7] The $\log(g_\ell f_{\ell u})_{CB}$ in column 8 are from CORLISS and BOZMAN.[9] Solar equivalent widths measured on the KPNO spectrum are listed in column 9. The solar equivalent widths in column 10 are from MOORE et al.,[10] except those identified with superscript GB which are from GREVESSE and BLANQUET.[11] A question mark following a width of MOORE et al. designates a line which they identified as Nd (II)?

Table 1

Upper Level (E_u[cm^{-1}]) τ	λ[Å]	RMT No.	Lower Level	(BR) [%]	A_{ul}[$10^6 s^{-1}$]	$\log(g_l f_{lu})$	$\log(g_l f_{lu})_{CB}$	W_{KP}[mÅ]	W_{Other}[mÅ]	$\log(N_{Nd}/N_H) + 12$
$w^6K^o_{9/2}[z^6K^o_{9/2}]$	4303.573	10	$a^6I_{7/2}$	61.0	47.0	+0.12	-0.47		65	
(23229.99)	4400.828	10	$a^6I_{9/2}$	8.8	6.8	-0.71	-1.44			
13 ± 3 ns	4632.688	—	$a^4I_{9/2}$	1.3	1.0	-1.50	-2.41			
	4958.139	—	$a^4I_{11/2}$	1.5	1.2	-1.37	-2.02			
	5319.818	75	$a^6L_{11/2}$	20.2	15.6	-0.18	-0.96	9.62	11, 9.3^{GB}	1.21
	5804.020	79	$a^6K_{9/2}$	6.0	4.6	-0.64	-1.33			
	6133.964	—	$a^6K_{11/2}$	0.3	0.2	-1.86	—			
	6365.554	—	$b^6I_{7/2}$	0.9	0.7	-1.39	-2.17			
$w^6K^o_{13/2}[z^6K^o_{13/2}]$	4156.083	10	$a^6I_{11/2}$	36.7	34.4	+0.10	-0.49		30	
(25524.49)	4358.169	10	$a^6I_{13/2}$	16.4	15.4	-0.21	-0.98		38	
[10.7 ns]	4451.566	50	$a^4I_{11/2}$	27.1	25.4	+0.02	-0.75			
	4602.242	—	$a^6I_{15/2}$	0.4	0.4	-1.79	—			
	5293.168	75	$a^6L_{15/2}$	12.7	12.0	-0.15	-0.55	9.91	10, 9.4^{GB}	1.46
	5688.525	79	$a^6K_{13/2}$	6.3	5.9	-0.40	-0.85			
	6183.907	—	$b^6I_{11/2}$	< 0.5	< 0.4	< -1.45	-1.75			
$w^6K^o_{15/2}[z^6K^o_{15/2}]$	4109.455	10	$a^6I_{13/2}$	38.4	37.4	+0.18	-0.41		39	
(26912.77)	4325.766	10	$a^6I_{15/2}$	15.9	15.5	-0.16	-0.71			
[10.3 ns]	4462.985	50	$a^4I_{13/2}$	18.4	17.9	-0.07	-0.84	13.08	13	1.30
	5249.585	75	$a^6L_{17/2}$	18.4	17.9	+0.07	-0.37	9.92	11	1.38
	5594.425	79	$a^6K_{15/2}$	7.2	7.0	-0.28	-0.77			
	6031.266	—	$b^6I_{13/2}$	1.7	1.7	-0.83	-1.49		2?	
$w^6K^o_{17/2}[z^6K^o_{17/2}]$	4061.085	10	$a^6I_{15/2}$	53.3	44.4	+0.30	+0.03			
(28418.97)	4284.518	10	$a^6I_{17/2}$	10.3	8.5	-0.37	-0.73	4.46	8.5	1.15
12 ± 3 ns	4456.394	50	$a^4I_{15/2}$	7.7	6.4	-0.46	-1.04			
	5192.621	75	$a^6L_{19/2}$	20.0	16.6	+0.08	-0.25	5.97	14	1.30
	5485.699	79	$a^6K_{17/2}$	6.8	5.7	-0.34	-0.75	5.67	2.5	1.80
	5865.057	—	$b^6I_{15/2}$	1.6	1.3	-0.90	-1.34			
	6264.34	—	$b^6I_{17/2}$	0.3	0.2	-1.58	—			
$w^6K^o_{19/2}[z^6K^o_{19/2}]$	4012.250	10	$a^6I_{17/2}$	71.2	54.8	+0.42	+0.10		39	
(30002.30)	5150.596	75	$a^6L_{21/2}$	20.9	16.1	+0.10	-0.05			
13 ± 3 ns	5371.935	79	$a^6K_{19/2}$	6.7	5.1	-0.35	-0.63	7.02	9	2.06
	5698.927	—	$b^6I_{17/2}$	1.1	0.9	-1.07	-1.08			
$x^6I^o_{9/2}[17^o_{9/2}]$	3863.327	27	$a^6I_{7/2}$	15.4	15.4	-0.46	-0.45			
(25877.18)	3941.512	27	$a^6I_{9/2}$	60.8	60.8	+0.15	-0.69			
10 ± 3 ns	4095.999	—	$a^6I_{11/2}$	0.3	0.3	-2.12	—			
	4126.475	—	$a^4I_{9/2}$	0.9	0.9	-1.63	—			
	4382.737	—	$a^4I_{11/2}$	4.0	4.0	-0.94	-1.79			
	5276.879	81	$a^6K_{11/2}$	11.9	11.9	-0.30	-1.19		1.5, 1.5^{GB}	
	5726.825	—	$b^6I_{9/2}$	5.6	5.6	-0.56	-1.44			
	6051.875	—	$b^6I_{11/2}$	1.1	1.1	-1.24	—			

Table 1

cont'd

Upper Level (E_u[cm^{-1}]) τ	λ[Å]	RMT No.	Lower Level	(BR) [%]	A_{ul}[$10^6 s^{-1}$]	$\log(g_l f_{lu})$	$\log(g_l f_{lu})_{CB}$	W_{KP}[mÅ]	W_{Other}[mÅ]	$\log(N_{Nd}/N_H) + 12$
$x^6I^o_{11/2}[y^6I^o_{11/2}]$	3807.227	19	$a^6I_{9/2}$	3.7	4.9	-0.89	-1.26			
(26772.09)	3951.154	19	$a^6I_{11/2}$	45.5	60.1	+0.23	-0.58			
[7.6 ns]	3979.479	57	$a^4I_{9/2}$	20.6	27.2	-0.11	-1.00			
	4133.361	19	$a^6I_{13/2}$	11.2	14.7	-0.34	-1.15	9.26	11	1.22
	4217.282	57	$a^4I_{11/2}$	1.8	2.4	-1.12	-1.73			
	5311.461	80	$a^6K_{13/2}$	8.6	11.4	-0.24	-0.89	2.95	2.5, 2.4^{GB}	1.17
	5447.556	–	$b^6I_{9/2}$	1.0	1.3	-1.15	-1.64			
	5740.862	86	$b^6I_{11/2}$	5.4	7.2	-0.37	-1.27			
	6082.96	–	$b^6I_{13/2}$	2.2	2.9	-0.71	–			
$x^6I^o_{15/2}[y^6I^o_{15/2}]$	3805.359	19	$a^6I_{13/2}$	39.8	69.4	+0.38	–			
(28856.90)	3990.103	19	$a^6I_{15/2}$	29.8	52.0	+0.30	-0.46		27, 17.3^{GB}	
[5.7 ns]	4106.582	57	$a^4I_{13/2}$	3.9	6.8	-0.56	-1.27			
	4205.595	19	$a^6I_{17/2}$	10.2	17.7	-0.12	-0.87			
	4371.069	57	$a^4I_{15/2}$	0.8	1.4	-1.21	–			
	5356.976	80	$a^6K_{17/2}$	10.6	18.4	+0.10	-0.70	2.15	2 ?, 2.9^{GB}	0.95
	5718.120	86	$b^6I_{15/2}$	5.0	8.7	-0.17	-0.97	1.78	4 ?	1.24
$x^6I^o_{17/2}[y^6I^o_{17/2}]$	3780.391	19	$a^6I_{15/2}$	13.4	14.0	-0.27	-0.76			
(30246.77)	3973.269	19	$a^6I_{17/2}$	60.6	63.2	+0.43	-0.41		11	
[9.6 ns]	4120.654	57	$a^4I_{15/2}$	2.4	2.5	-0.97	-1.48			
	5302.279	80	$a^6K_{19/2}$	10.9	11.3	-0.07	-0.59			
	5620.62	86	$b^6I_{17/2}$	12.7	13.3	+0.05	–		2	

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FIGURE CAPTIONS

Fig. 1. Logarithm of the ratio of the transition probability A_{CB} of CORLISS and BOZMAN[9] to that reported in this paper (A_{CIT}), plotted as a function of wavelength. The full circles represent the ten lines used in the solar abundance determination. The crosses represent $\lambda\lambda$ 5372 and 5468.

Fig. 2. Logarithm of the ratio of the transition probability A_{CB} of CORLISS and BOZMAN[9] to that reported in this paper (A_{CIT}), plotted as a function of the strength of the transition. The full circles represent the ten lines used in the solar abundance determination. The crosses represent $\lambda\lambda$ 5372 and 5468.

Fig. 3. Logarithm of the ratio of the transition probability A_{CB} of CORLISS and BOZMAN[9] to that reported in this paper (A_{CIT}), plotted as a function of the excitation energy of the upper level. The full circles represent the ten lines used in the solar abundance determination. The crosses represent $\lambda\lambda$ 5372 and 5468.

Fig. 4. Solar Nd (II) curve of growth for weak lines at the center of the disk. The crosses represent $\lambda\lambda$ 5372 and 5468. The crosses have been disregarded in drawing the line which represents our best estimate of the solar Nd abundance : $\log (N_{Nd}/N_H) = -10.74$.

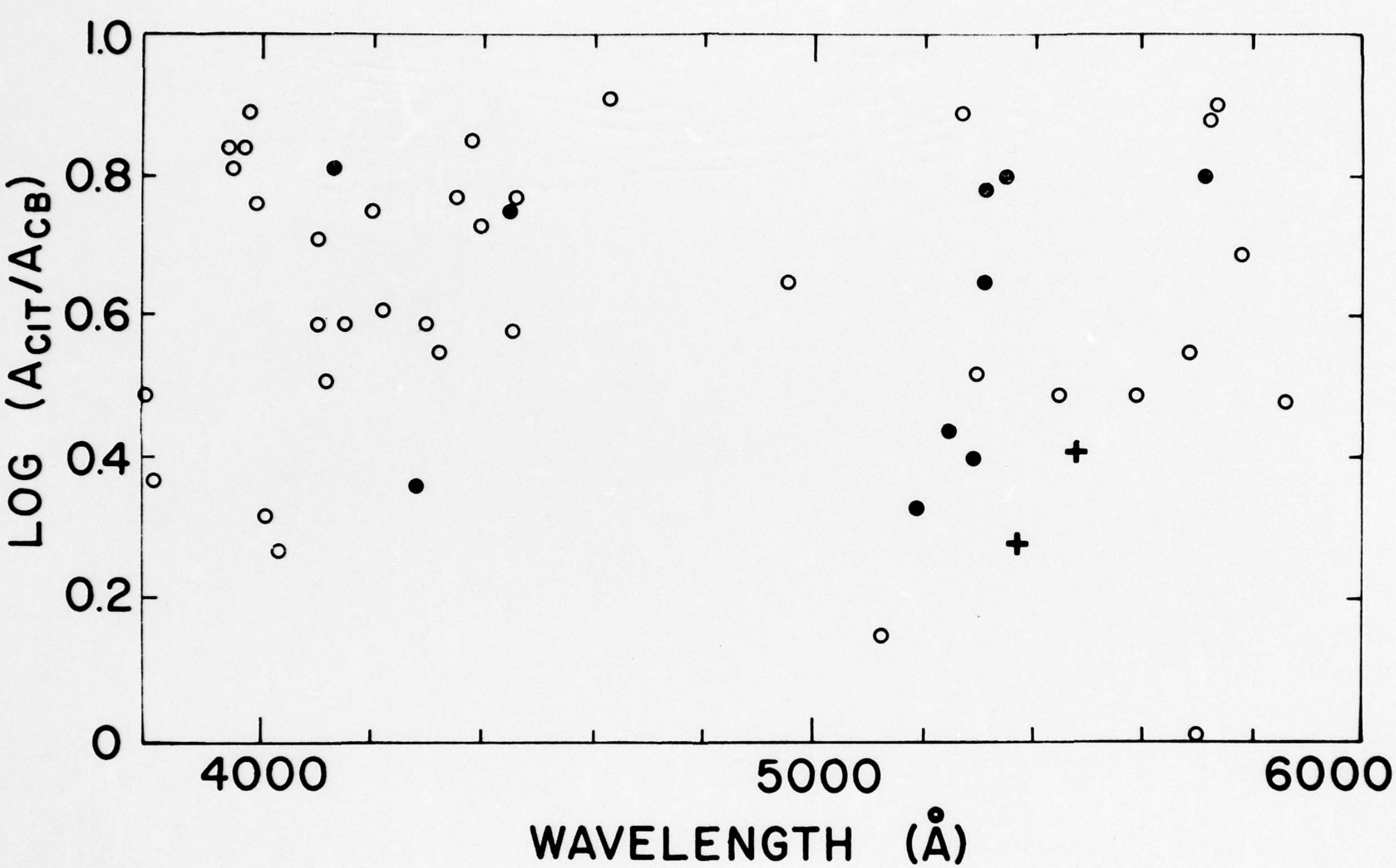

Fig. 1

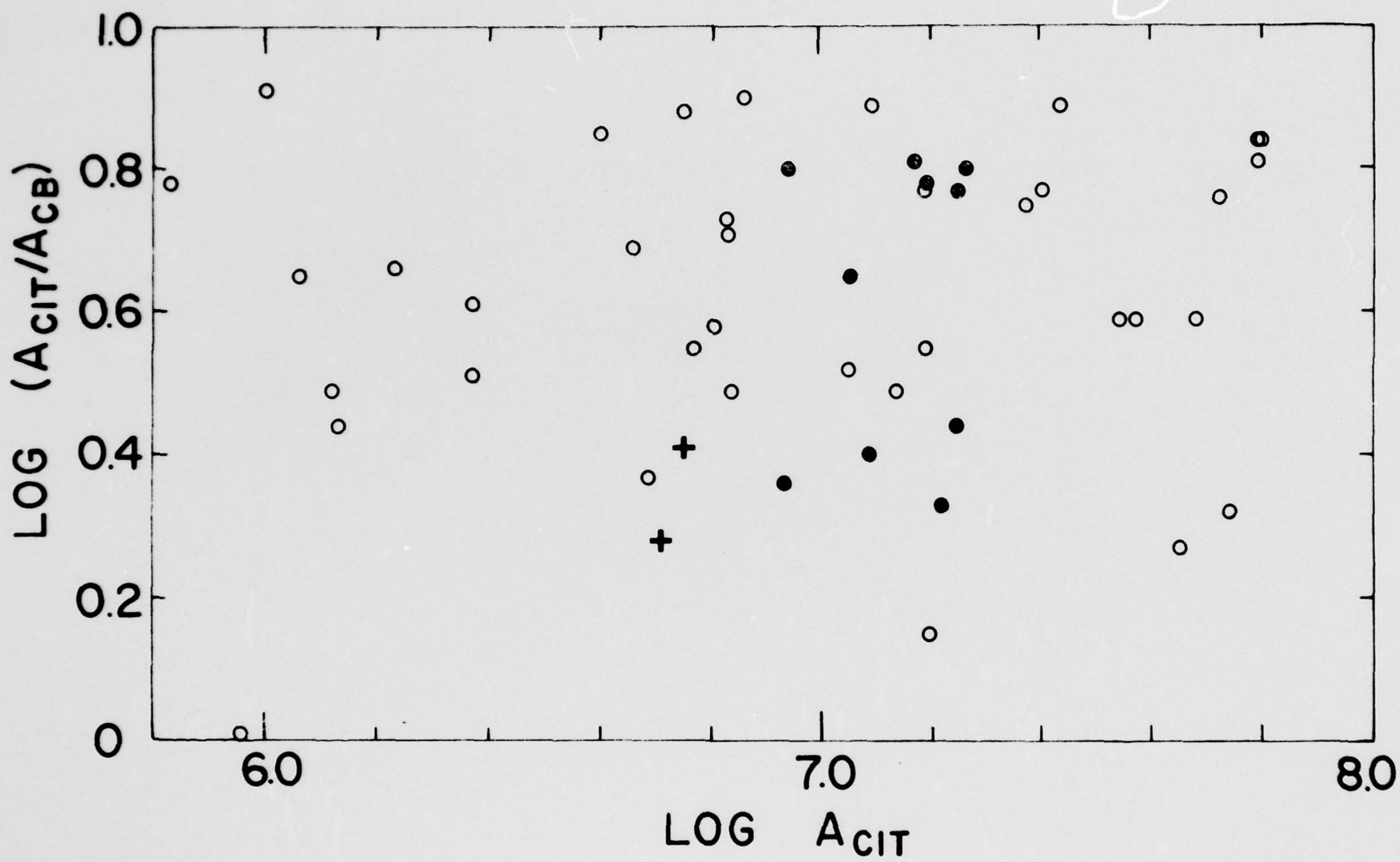

Fig 2

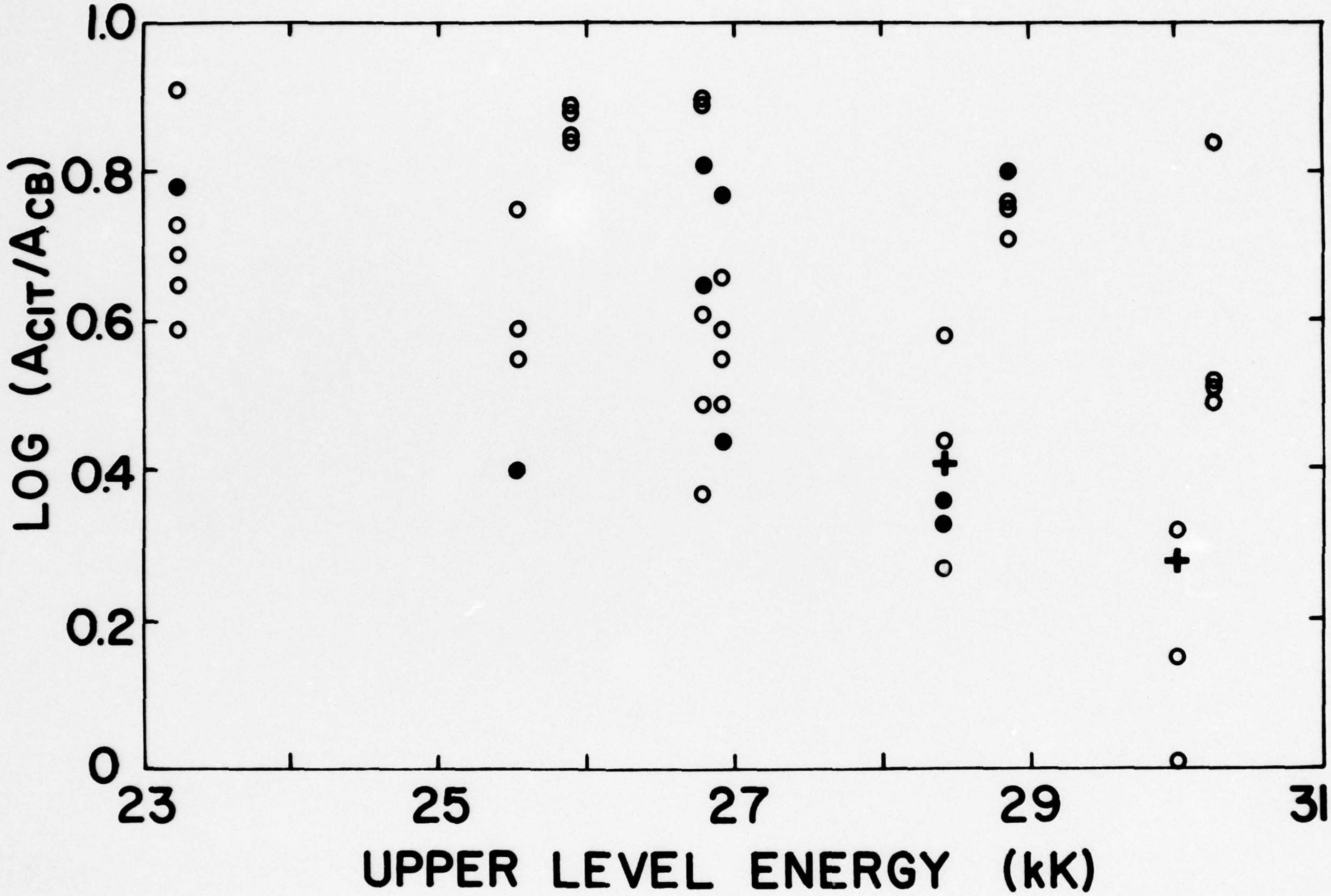

Fig. 3

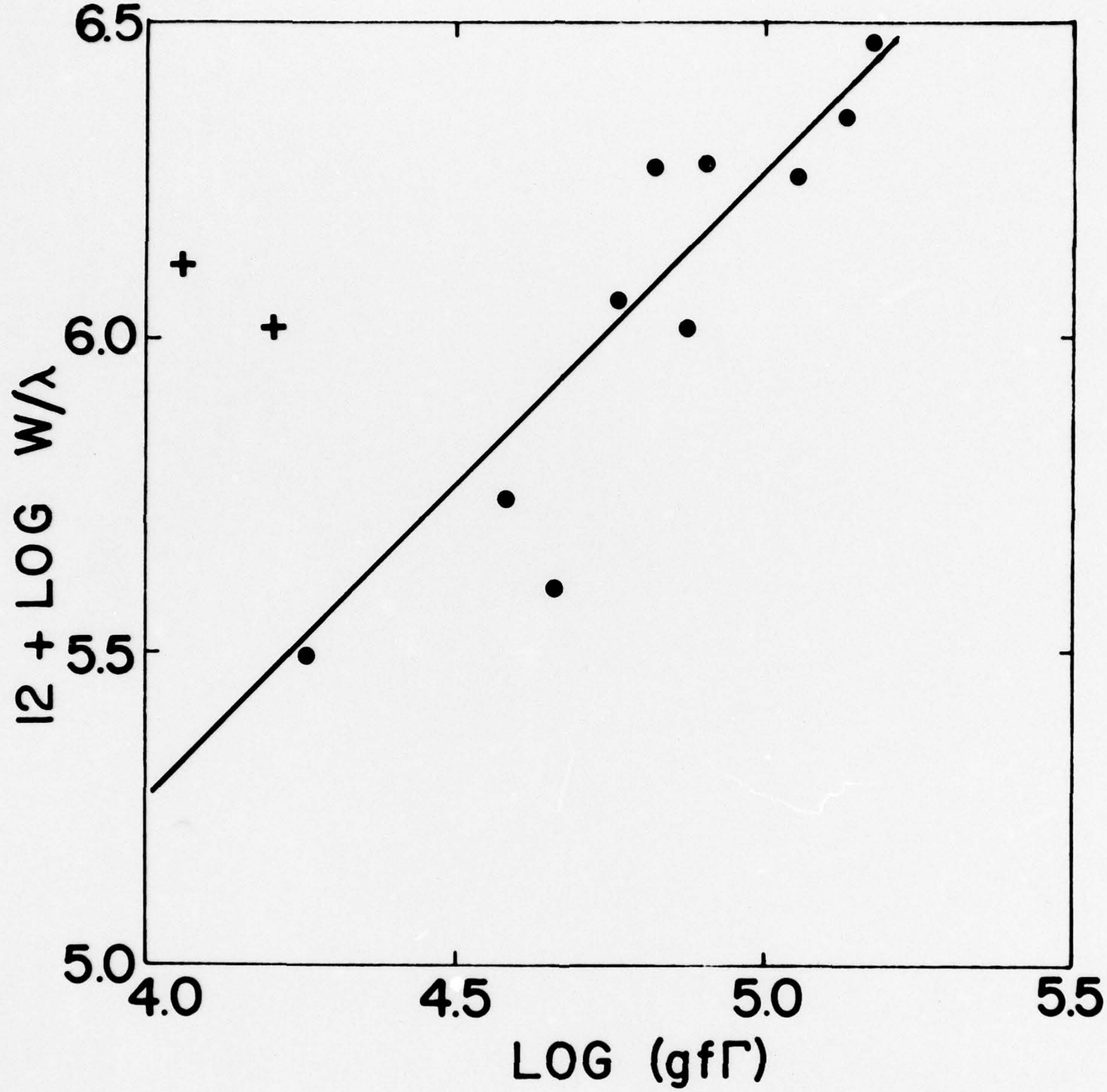

Fig. 4